Acceleration and loss of relativistic electrons during geomagnetic storms

G. D. Reeves, K. L. McAdams, and R. H. W. Friedel

Space and Atmospheric Sciences Group, Los Alamos National Laboratory, Los Alamos, New Mexico, USA

T. P. O'Brien

Space Sciences Department, The Aerospace Corporation, Los Angeles, California, USA

Received 24 October 2002; revised 18 December 2002; accepted 21 March 2003; published 27 May 2003.

[1] We analyze the response of relativistic electrons to the 276 moderate and intense geomagnetic storms spanning the 11 years from 1989 through 2000. We find that geomagnetic storms can either increase or decrease the fluxes of relativistic electrons in the radiation belts. Surprisingly, only about half of all storms increased the fluxes of relativistic electrons, one quarter decreased the fluxes, and one quarter produced little or no change in the fluxes. We also found that the pre-storm and post-storm fluxes were highly uncorrelated suggesting that storms do not simply "pump up" the radiation belts. We found that these conclusions were independent of the strength of the storm (minimum Dst) and independent of L-shell. In contrast, we found that higher solar wind velocities increase the probability of a large flux increase. However, for all solar wind velocities both increases and decreases were still observed. Our analysis suggests that the effect of geomagnetic storms on radiation belt fluxes are a delicate and complicated balance between the effects of particle acceleration and loss. *INDEX TERMS:* 2788 Magnetospheric Physics: Storms and substorms; 2730 Magnetosphere—inner; 2720 Energetic particles, trapped; 2716 Energetic particles, precipitating. **Citation:** Reeves, G. D., K. L. McAdams, R. H. W. Friedel, and T. P. O'Brien, Acceleration and loss of relativistic electrons during geomagnetic storms, *Geophys. Res. Lett.*, *30*(10), 1529, doi:10.1029/2002GL016513, 2003.

1. Introduction

[2] The dynamics of the radiation belts have received considerable attention in recent years because of their impact on life in our technology-based society and because of the fundamental and unresolved scientific questions about the acceleration and loss of radiation belt particles. In this study we examine a full solar cycle of data (1989–2000) to quantify the relationship between geomagnetic storms and relativistic electron flux increases and decreases.

[3] In a predecessor to this study, *Reeves* [1998] examined three years (1992–1994) of relativistic electron fluxes from geosynchronous orbit and compared changes in those fluxes with storm activity measured by the Dst index. Reeves found that each distinct electron enhancement was associated with a distinct decrease in the Dst index. This clearly established a connection between storms and relativistic electron enhancements. Reeves also found that approximately 10% of those storms were not accompanied by increases in the geosynchronous relativistic (1.8–3.5 MeV) electron fluxes. Additionally, while larger relativistic electron fluxes tended to occur during larger storms, the correlation was quite weak. (We also note that, in contrast to this study, *Reeves* [1998] included storms with minimum Dst as weak as −20 nT.)

[4] Previous studies have focused on increases in relativistic electron fluxes. However, dramatic decreases in electron fluxes can also be observed during storms. The most common decrease is a temporary, adiabatic 'dropout' of electron fluxes associated with the 'Dst Effect' [e.g., *Kim and Chan*, 1997]. However, during some storms the electron fluxes never regain their pre-storm levels [e.g., *Onsager et al.*, 2002; *O'Brien et al.*, 2001a]. *Friedel et al.* [2002] provide a more complete review of relativistic electron acceleration and loss mechanisms.

2. Data Sets

[5] Geosynchronous data are 1.8–3.5 MeV electron fluxes from the Los Alamos National Laboratory (LANL) space environment monitors. To minimize the effects of daily local time variation caused by magnetic field asymmetries [e.g., *Reeves et al.*, 1998a] we apply a statistical reconstruction of the fluxes to a common local time which is chosen to be noon. This is the same technique and the same data set used by *O'Brien et al.* [2001b]. One-hour resolution data from multiple satellites are averaged to obtain a single consistent time series.

[6] A broader measurement of the radiation belts is provided by L-shell sorted 1.2–2.4 MeV electron data from the HIST instrument on POLAR [*Blake et al.*, 1995]. To minimize the effect of errors in calculating L in the asymmetric geomagnetic field we use only data from the northern hemisphere, inbound quadrant of the POLAR orbit. POLAR data are only available from late 1996 onward and we use data through 2000. We calculate "L" using the Kp = 2 version of the static Tsyganenko 1997 magnetic field model. Therefore "L" here should be considered to be an indication of spatial location rather than an invariant of particle drift motion.

[7] As a general measure of storm intensity we use the 1-hour resolution Dst index for 1989 through 2000. (Preliminary Dst data were used for 1999–2000.) For solar wind velocity we use 1-hour values from the OMNI database.

3. Increases and Decreases in Relativistic Electron Fluxes During Storms

[8] Throughout this analysis we start by identifying geomagnetic storms and then investigate the relativistic

0094-8276/03/2002GL016513$05.00

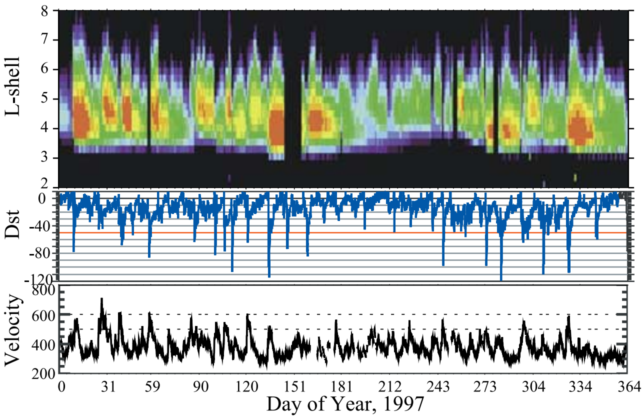

Figure 1. Radiation belt electron fluxes as a function of L-shell and time, the hourly Dst index (with our −50 nT threshold marked in red), and solar wind velocity.

electron response. In contrast to the earlier study of *Reeves* [1998], we use a fixed definition of geomagnetic storms as distinct intervals during which the minimum value of the Dst index is less than −50 nT. *Gonzalez et al.* [1994] define these storms as moderate (Dst < −50 nT) or intense (Dst < −100 nT).

[9] Figure 1 shows the relativistic electron fluxes (1.2–2.4 MeV) measured by POLAR as a function of L-shell and time for the year 1997. Also shown are the Dst index and the solar wind velocity. The −50 nT Dst threshold is indicated with a red line. There were 21 storms during 1997 which met our criteria.

[10] Figure 2 shows three examples of the relativistic electron response to geomagnetic storms. Figure 2a shows the interval from January 1 to February 25, 1997 which includes the well-known January 10, 1997 storm [e.g., *Reeves et al.*, 1998a, 1998b; *Li et al.*, 1998]. This storm is typical of the storms that most studies have analyzed to date. A brief decrease of the relativistic electrons is observed in association with the build-up of the ring current but is quickly followed by a rapid increase of the electron fluxes over a broad range of L-shells.

[11] The storm in May 1999 (Figure 2b) shows a quite different response. Again there is a rapid decrease in fluxes at the storm main phase but, in this event, the fluxes never recovered to their pre-event levels. This cannot be explained by adiabatic processes and must therefore represent a true loss of particles. We note that the decrease in fluxes was observed over a broad range of L-shells down to at least L = 4. In February, 1998 (Figure 2c) a geomagnetic storm which qualifies as "intense" (Dst = −100 nT) by the Gonzalez et al. definition, produced a relatively small change in the relativistic electron fluxes.

3.1. Geosynchronous Flux Statistics

[12] To statistically analyze the relativistic electron response to geomagnetic storms we need to quantify the amount of increase or decrease in the fluxes. To do so, we first examine the fluxes at geosynchronous orbit which is at a fixed L-shell, L ≈ 6.6. The 24-hour period centered on the time of minimum Dst is considered the 'day of the storm' and is not included in the analysis. We define the 'pre-storm flux' as the maximum flux of 1.8–3.5 MeV electrons in the 1–3 days prior to storm (not including the day of the storm). We define the 'post-storm flux' as the maximum flux in the 1–5 days after the storm. We the calculate the ratio of the pre-storm to post-storm fluxes. We define "No Change" to mean that the relative change was less than a factor of 2 up or down. By these criteria 10 of the 21 events in 1997 (Figure 1) were classified as geosynchronous "increases," 5 were classified as "decreases," 5 were classified as "no change," and one storm, on May 15, had missing data and was not included in the analysis.

[13] In Figure 3a we plot the post-storm flux against the pre-storm flux and color each point: red for "increase," blue for "decrease," and green for "no change." One clear conclusion from this plot is that the pre-storm and post-storm fluxes are essentially uncorrelated. Any given post-storm flux could have been preceded by either high or low pre-storm levels.

[14] Figure 3b shows the distribution of events as a function of the change in flux (the ratio of post-storm to pre-storm fluxes). Over one entire solar cycle from 1989 through 2000 there were 276 storms with Dst < −50 for which we had complete geosynchronous data (noon reconstructed fluxes). Of those, 145 storms (53%) resulted in an increase in geosynchronous fluxes. Another 53 storms (19%) resulted in a flux decrease. For the remaining 78 storms (28%) changed the fluxes by less than a factor of 2 in either direction (no change).

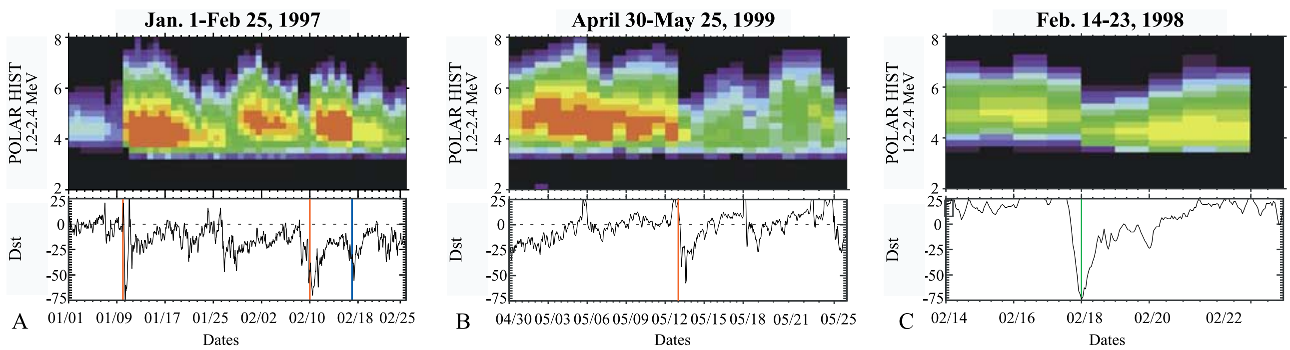

Figure 2. Details of three types of responses. (A) A strong increase of relativistic electron fluxes in response to the January 1997 geomagnetic storm. (B) A dramatic and permanent loss of electrons throughout the outer belt in May 1999. (C) A −100 nT storm in February 1998 with peak fluxes after the storm very similar to peak fluxes after the storm.

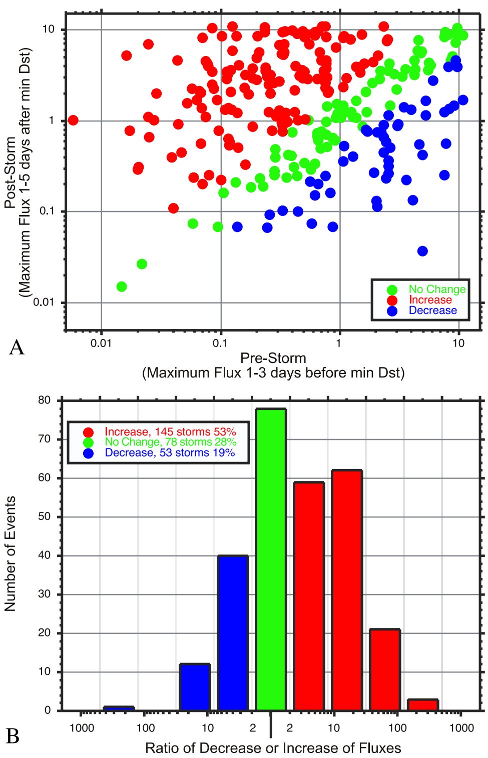

Figure 3. Statistics of geosynchronous flux changes for 1989 through 2000. (A) Post-storm peak fluxes and pre-storm peak fluxes are highly uncorrelated showing that the radiation belts are not simply "pumped up" during geomagnetic storms. (B) The distribution of the ratio of post-storm to pre-storm fluxes.

[15] Thus, we find that only about half of all storms produce a significant increase in relativistic electron fluxes. We also find the somewhat surprising result that approximately 1 in every 5 storms will decrease the fluxes by more than a factor of 2. It is also interesting to note the distribution of extreme changes. Six of the storms produced increases of more than two orders of magnitude and one produced an equally dramatic decrease.

3.2. Other Statistical Dependencies

[16] Are larger storms more likely to produce increases? It is commonly assumed that they do. To test this assumption we binned the 276 storms in our study according to their minimum Dst. In Figure 4a we plot the cumulative probability distribution as a function of the flux ratio (post/pre) for each range of Dst. The cumulative probability is the probability that the flux ratio will be less than a given value. The maximum difference in the cumulative probability curves, Δ, is marked in each plot and is a measure of how different the probabilities are and S is a measure of how likely it is that the difference is random.

[17] Figure 4a shows that the probability distributions for all four curves are essentially identical. Therefore the probability that the fluxes will increase (or decrease) by a given amount is essentially independent of the minimum value of Dst. Larger storms are not more likely to increase the relativistic electron fluxes than smaller storms.

[18] Does the chance of an increase depend on L-shell? It is relevant to ask if the results in section 3.1 based on geosynchronous fluxes are representative of the radiation belt response as a whole. We have performed a similar analysis to the one presented here on electron fluxes measured at different L-shells and we find that the results are essentially independent where the electron fluxes are measured.

[19] In this brief report we show only the cumulative probability as a function of flux ratio for fluxes measured by POLAR at L = 4, 5, 6, and 7 (Figure 4b). Each bin is $L = \pm 0.2$ wide. The probability curves for L = 4, 5, and 6 are nearly identical and only the L = 7 curve is significantly different. Due to measurement uncertainties at high L values is unclear at this stage whether the difference in the L = 7 curve is meaningful.

[20] The probability that a given storm will increase or decrease the fluxes of relativistic electrons is essentially the same whether the fluxes are measured at the heart of the outer belt at $L \approx 4$ or at geosynchronous orbit, $L \approx 6.6$.

[21] Does high solar wind velocity produce more increases? The relationship between high-speed solar wind streams and increases in the relativistic electron fluxes in the outer belts is probably the most widely known result concerning the radiation belts. In Figure 4c we separate the events according to the maximum solar wind velocity observed during the event (which could occur either before or after the storm main phase).

[22] There is a higher probability of increasing fluxes for higher solar wind velocities than for lower velocities. The maximum difference in the curves, Δ, is 31% which is very unlikely to be random (S = 1%). We also see that throughout the distributions the higher-velocity events produce larger increases in flux.

[23] Nevertheless, both high-speed and low-speed solar wind drivers can and do produce both increases and decreases in flux. Approximately 25–35% of all events produce no change or a decrease in fluxes regardless of solar wind velocity.

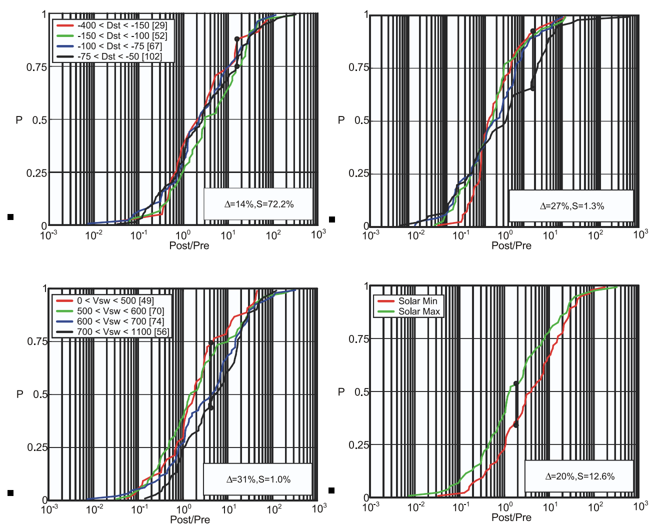

Figure 4. Cumulative probability distributions for the post- to pre-storm flux ratios binned by (A) minimum Dst, (B) different L-shells, (C) solar wind velocity, and (D) phase of the solar cycle. All show both increases and decreases in flux for all values of each parameter.

[24] Since solar wind velocity does appear to affect the chance of producing a radiation belt flux increase, we compared the years 1992–1994 ("solar minimum") with the years 1990, 1999, and 2000 ("solar maximum"). Figure 4d shows that, indeed, storms in our "solar minimum" years were more likely to produce larger increases, but, that difference is not as large as when solar wind velocity alone is used as a discriminator.

4. Conclusions and Implications for Understanding Electron Acceleration and Loss

[25] We have examined the response of relativistic electrons (≈1–3 MeV) in the outer radiation belts to 276 geomagnetic storms spanning the 11 years from 1989 to 2000. By definition we chose storms that were "moderate" (Dst < −50 nT) or "intense" (Dst < −100 nT).

[26] The most significant conclusion from this study is that geomagnetic storms can either increase or decrease the fluxes of relativistic electrons in the radiation belts. We found that about half (53%, 145 events) of the geomagnetic storms increased the fluxes; about one in five storms (19%, 53 events) decreased the fluxes; and the remaining storms (28%, 78 events) produced changes that were less than a factor of two either up or down. While it has been known that some storms produce a decrease in geosynchronous electron fluxes the number of such storms is a new and somewhat surprising result with important implications for forecasting radiation belt enhancements and for understanding acceleration and loss.

[27] When we compare the pre-storm and post-storm fluxes for these 276 storms we find that there is essentially no correlation between them (Figure 3a). This implies that the fluxes in the radiation belts are not simply "pumped up" during storm times. Equally intense post-storm fluxes can be produced out of nearly any pre-existing population.

[28] Of course, acceleration in the radiation belts is a process that energizes lower-energy electrons to relativistic energies, often transporting them across L-shells at the same time. Therefore, comparing pre- and post-storm flux levels at fixed energy and L-shell is not a rigorous technique for quantifying the amount of acceleration. Rather, the flux produced by an acceleration event will be a function of the fluxes of the lower-energy source population and the amount of radial transport. This study re-emphasizes the fact that neither the change in fluxes nor the absolute post-storm flux level precisely quantifies the amount of acceleration in a given event.

[29] Our results also highlight the importance of relativistic electron losses during geomagnetic storms. The losses we discuss here are not temporary, adiabatic responses (the 'Dst effect') but, rather, real loss of electrons to the magnetopause or to the ionosphere. Ionospheric loss, i.e. precipitation, is more likely because the losses are observed down to very low L-shell even when the magnetopause remains well outside geosynchronous orbit.

[30] We found that the conclusions based on geosynchronous data were general regardless of whether the fluxes are measured at L = 4, 5, 6, or 6.6. We investigated the hypothesis that larger storms (lower minimum Dst) would be more likely to increase relativistic electron fluxes than more moderate storms. We found that, although it is widely assumed to be true, this was not the case. Over the range of minimum Dst values from −50 to −400 nT the probability that a storm will increase or decrease the fluxes was independent of Dst. In contrast sorting events by maximum solar wind velocity shows that it is more likely that high-speed solar wind drivers will produce larger increases in the electron fluxes. However, even storms with high-speed solar wind can produce dramatic decreases in relativistic electron populations.

[31] It appears that the magnitude of acceleration and loss are comparable, may act simultaneously, and each may have effects that vary by orders of magnitude. Like subtraction of very large numbers, one or another may dominate in a given storm. What emerges from these observations is the conclusion that electron loss and acceleration processes are both enhanced during geomagnetic storms and the fluxes that are observed following the storm are a delicate balance between the amount of acceleration and the amount of loss.

[32] **Acknowledgments.** We thank Kyoto University for providing the Dst data, the NSSDC for providing solar wind data, and J. B. Blake and the POLAR CEPPAD instrument team for the HIST electron data. We thank the National Science Foundation, the National Aeronautics and Space Administration, and the Los Alamos Institute of Geophysics and Planetary Physics for financial support of this work.

References

Blake, J. B., et al., CEPPAD: Comprehensive Energetic Particle and Pitch Angle Distribution experiment on POLAR, *Space Sci. Rev.*, *71*, 531–562, 1995.

Friedel, R. H. W., G. D. Reeves, and T. Obara, Relativistic electron dynamics in the inner magnetosphere: A review, *J. Atmos. Solar-Terrestrial Phys.*, *64*, 265–282, 2002.

Gonzalez, W. D., et al., What is a geomagnetic storm?, *J. Geophys. Res.*, *99*, 5771–5792, 1994.

Kim, H.-J., and A. A. Chan, Fully-adiabatic changes in storm-time relativistic electron fluxes, *J. Geophys. Res.*, *102*, 22,107, 1997.

Li, X., et al., Energetic electron injections into the inner magnetosphere during the January 10–11, 1997 magnetic cloud event, *Geophys. Res. Lett.*, *25*, 2561, 1998.

O'Brien, T. P., et al., Which magnetic storms produce relativistic electrons at geosynchronous orbit?, *J. Geophys. Res.*, *106*, 15,533–15,544, 2001a.

O'Brien, T. P., D. Sornette, and R. L. McPherron, Statistical asynchronous regression: Determining the relationship between two quantities that are not measured simultaneously, *J. Geophys. Res.*, *106*, 13,247–13,259, 2001b.

Onsager, T. G., et al., Radiation Belt Electron Flux Dropouts: Local Time, Radial, and Particle-Energy Dependence, *J. Geophys. Res.*, in press, 2002.

Reeves, G. D., Relativistic electrons and magnetic storms: 1992–1995, *Geophys. Res. Lett.*, *25*, 1817, 1998.

Reeves, G. D., et al., The Relativistic Electron Response at Geosynchronous Orbit During the January 1997 Magnetic Storm, *J. Geophys. Res.*, *103*, 17,559, 1998a.

Reeves, G. D., et al., The Global Response of Relativistic Radiation Belt Electrons to the January 1997 Magnetic Cloud, *Geophys. Res. Lett.*, *17*, 3265–3268, 1998b.

R. H. W. Friedel, K. L. McAdams, and G. D. Reeves, Space and Atmospheric Sciences Group, Los Alamos National Laboratory, Los Alamos, NM 87545, USA. (reeves@lanl.gov)

T. P. O'Brien, Space Sciences Department, The Aerospace Corporation, Los Angeles, CA 90009, USA.